A Score Function Heuristic for Crosstalk- and Fragmentation-Aware Dynamic Routing, Modulation, Core, and Spectrum Allocation in SDM-EONs

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***Abstract*—The effects of crosstalk and fragmentation cause unnecessary blocking in space-division multiplexing-based elastic optical networks. A routing, modulation, core, and spectrum allocation (RMCSA) algorithm is proposed in this paper using a novel score function that balances the crosstalk and fragmentation. Reduced blocking and fragmentation levels are observed when compared with the benchmark algorithms.**

***Index Terms*—SDM-EONs, RMCSA, crosstalk, fragmentation, score function**

I. Introduction

Optical transmission systems and networks are crucial in connecting the worldwide communications infrastructure. The rise in the number of devices, innovative applications, and machine-to-machine communication needs will cause a two-four times increase in traffic in the next two to four years [1]. Therefore, communication networks need to be used efficiently to accommodate the growing network traffic of 5G and beyond. During the last few years, elastic optical networks (EONs) have been investigated as a promising solution to the inefficient spectrum utilization of traditional wavelength-division multiplexing (WDM) optical networks. However, the currently deployed single-mode fiber capacity is nearly exhausted. A good solution is to utilize multi-core fibers (MCFs) to exploit the spatial domain, creating a space division multiplexed elastic optical network (SDM-EON). This paper proposes a resource allocation algorithm for SDM-EONs that accounts for both fragmentation and physical layer impairments.

Inter-core crosstalk (XT) is a significant challenge when using MCFs. XT is the unwanted signal interaction between signals propagating on adjacent fiber cores that degrades the quality of transmission (QoT). Hence, the design of resource allocation algorithms for SDM-EONs should take XT into account. Many current studies [2]–[5] have proposed XT-aware routing, modulation, core, and spectrum allocation (RMCSA) algorithms. However, minimizing the XT can lead to network fragmentation, which results in network under-utilization.

Most networking studies calculate the worst-case XT levels, i.e., considering all neighbor cores as active. This approach is overly conservative and increases the blocking of incoming traffic demands. On the other hand, performing precise XT calculations on each spectrum slot on each core, as used in [2], [6], is overly time-consuming. A less time-consuming version can be found in [7]. However, the network fragmentation aspect is not considered by these researchers. A XT-aware RMCSA algorithm that assumes the worst-case XT is used as the benchmark in this current work.

We propose an XT- and fragmentation-aware heuristic algorithm for dynamic RMCSA. It uses a score function (SF) to rate a candidate spectrum block to help select the best spectrum block, route, modulation, and core while keeping the fragmentation levels low. The SF's score represents how resistant a particular spectrum block is to the expected XT and how it might affect existing signals w.r.t. XT and fragmentation. The proposed approach is tested on two commonly-used topologies and is shown to be superior when compared with the worst-case XT level benchmark, and two modified (for the current work) classical spectrum benchmarks that incorporate a crosstalk constraint, namely XT- aware First Fit and XT-aware Best Fit.

II. Crosstalk and Fragmentation Aware RMCSA

RMCSA, already known to be an NP-hard problem, is made even harder when XT is considered along with existing EON constraints of spectrum continuity and contiguity. Hence, heuristic resource allocation algorithms are needed. In SDM-EON systems, the XT tends to limit performance. In our work, the XT is estimated using the models provided in [7]. To

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ensure a sufficient QoT, a XT-threshold (XT_{th}) constraint, proposed in [3], is adopted, denoted as

$$XT(lp) < XT_{th}, \tag{1}$$

where $XT(lp)$ is the total end-to-end XT experienced by the signal of interest on lightpath lp. $XT(lp)$ is a summation of the XT on consecutive links e,

$$XT(lp) = \sum_{e \in lp} XT^{\max}(lp, e), \tag{2}$$

where

$$XT^{\max}(lp, e) = \max_{s} K(lp, e, s) \cdot h \cdot L(e). \tag{3}$$

$L(e)$ is the length of the fiber link e, and h is the power-coupling coefficient. $XT^{\max}(lp, e)$ is the XT of the most affected spectral slice of lightpath lp on link e. $K(lp, e, s)$ is the number of active adjacent cores to the core currently considered in spectral slot s on link e of lightpath lp.

Typical approaches to XT mitigation tend to allot the spectrum to avoid overlapping with existing signals, thereby avoiding inter-core XT effects. But this also causes fragmentation when traffic requests are provisioned dynamically, increasing the probability that future requests are blocked due to the unavailability of spectral resources. Consequently, fragmentation mitigation requires that spectrum slots be allocated compactly. Maintaining a balance between reducing XT and limiting fragmentation during RMCSA is necessary to keep the QoT high and the blocking low. Hence, a weighted combination of these two factors is considered in this paper.

Our algorithm begins by computing the K-shortest paths (KSP) and a score function based on spectrum blocks on respective cores. We define a weighted multi-objective function that computes a score for the feasible candidate spectrum block as described in Algorithm 1. This score is calculated for the entire route and considers the number of occupied slots surrounding the candidate block and the amount of fragmentation it could cause. Note that the score is calculated for the whole frequency block and not for each individual frequency slot, which would become computationally prohibitive. The lower the score for a candidate block, the lower the expected XT and the lower the fragmentation-causing capability. As seen from Algorithm 1, for each link, the first term, $C(e)$, denotes the score value considering XT and the second term, $F(e)$, denotes the score value relating to the additional fragmentation caused by selecting that particular spectral block. The weight α decides the importance given to XT versus fragmentation.

To see how the $F(e)$ term captures the spectral block's fragmentation-causing capability, consider a link having the occupancy distribution [ABCD111HIJKLM11PQRST11], where a '1' denotes an occupied slot and the letters are position indicators denoting available slots. Assume a block of size three is needed. Then, the candidate blocks are [ABC], [BCD], [HIJ], [IJK], [JKL], [KLM], [PQR], [QRS] and [RST]. Assume that these are available on all links of the candidate route as well, satisfying continuity. The classical spectrum allocation algorithms, First Fit (FF), last fit, exact fit and Best Fit (BF) [8] would choose [ABC], [RST], [ABC], and [ABC], respectively. However, choosing these blocks leaves fragments of sizes 1, 2, 1, and 1 respectively, which is wasteful w.r.t. future request accommodation. But the proposed approach would prefer (considering fragmentation alone) [HIJ] or [KLM] as they leave zero fragments with sizes less than the block being provisioned, thus leaving bigger blocks of contiguous available slots. The $F(e)$ term captures this by counting the number of such fragments created by a candidate block. This term, combined with the $C(e)$ term in a weighted manner, helps the algorithm choose the best block on the entire route while maintaining both the fragmentation and XT objectives.

Algorithm 1: Score_Function

Data: All cores, candidate routes, status of cores on links, chosen core, candidate spectral block
Result: Score of the candidate spectral block

For each link e of route lp
  $n_{occ}(e) =$ number of occupied frequency slots on adjacent cores overlapping the candidate block
  $C(e) = [n_{occ}(e) - (\text{number of slots needed}/2)]^2$
  $F(e) =$ number of fragments created with size less than the required slots
  $Y(e) = \alpha\ C(e) + (1 - \alpha)F(e)$
Score_Function(candidate block) = $\sum_{e \in lp} Y(e)$

Algorithm 2 shows the proposed approach. The score value is initialized to infinity in the beginning. After finding the least fragmented cores, the spectral blocks satisfying the continuity, and contiguity conditions are found. The Score_Function algorithm is called for the first candidate block and then compared with the previously stored block's value. If the new value is lower than the stored one, then XT is computed using (2). If it does not satisfy the threshold criterion in (1) or unduly degrades other established lightpaths, the search proceeds towards the next spectrum block and the Score_Function is called again. But if (1) is satisfied, then the current candidate block and its score are stored. Then, the procedure is repeated on the next cores. The idea behind this repetition is to include the best possible blocks found on other cores while limiting the search in the spectral space by stopping whenever an XT-satisfying scored block is found.

The complexity of the proposed algorithm is $O(KFMN)$, where, K is the number of routes considered, F is the number of frequency slots, M is the number of cores and N is the number of network nodes.

III. Simulation Results and Discussions

The proposed algorithm is tested on two network topologies, the 11-node and 52-link COST239 and the 14-node and 21-link NSFNET [4], with 7 cores MCF per link. Each core has a total of 320 frequency slots with each slot supporting 12.5 GHz transmission. A Poisson traffic distribution model is used

Algorithm 2: Score Function-Based RMCSA

Data: Source, destination, requested bandwidth
Result: Chosen route, core, and a spectrum block

1 **Start**
2 **Repeat over routes**
3 Calculate suitable modulation format
4 Set Stored_score = ∞, Stored_block = [ ]
5 **Repeat through list of cores**
6 Create list of candidate spectrum blocks satisfying the continuity and contiguity constraints
7 **Repeat through list of candidate blocks**
8 Call Score_Function to obtain the Current_score
9 **If** Current_score < Stored_score
Compute the XT using (2)
10 **If** (1) is satisfied and existing lightpaths not degraded
11 Stored_score = Current_score
12 Stored_block = Candidate_block
13 Go to step 7 and repeat above for next core
14 **Else**
15 Check next spectrum block
16 **Else**
17 Check on next core
18 Provision the request on the current route, core, and spectrum block
19 **Until** request is provisioned, or all cores checked
20 **Until** request is provisioned, or K routes checked

to generate 100,000 requests for varying loads with data rates uniformly distributed in $[50, 300]$ Gbps. Modulation selection is distance adaptive, and the set of formats considered are BPSK, QPSK, 8-QAM and 16-QAM with threshold XT values of -21.75 dB, -25.76 dB, -28.77 dB, and -31.79 dB, respectively [3]. The network fragmentation is computed using [9, Eq. (4)].

The value of $\alpha \in [0, 1]$ is set to 0.5 for the results presented here. From various combinations tested, the value $\alpha = 0.5$ provided the best performance considering all the loads, and hence, it is chosen for the proposed algorithm. Table I shows that extreme end values of α worsen the blocking probability since, at both values, either only the fragmentation or XT is given importance, whereas both are prime causes for traffic rejections.

TABLE I
BLOCKING PROBABILITY FOR VARIOUS VALUES OF α USING SCORE FUNCTION-BASED RMCSA ON COST239 NETWORK

	Traffic Load (Erlangs)		
α	*400*	*600*	*800*
0	0.00209	0.00437	0.00901
0.5	0.00130	0.00256	0.00748
1	0.00222	0.00446	0.00917

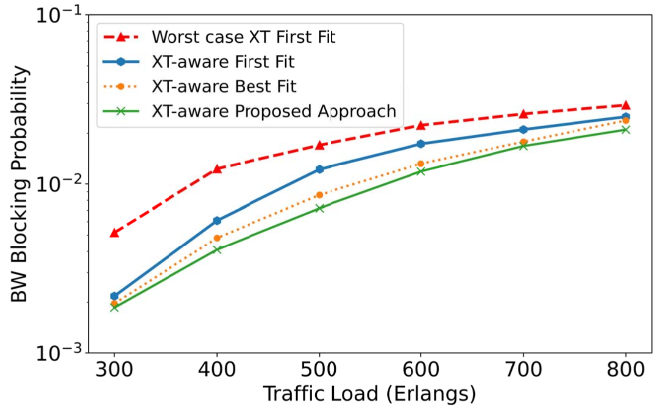

Fig. 1. Bandwidth blocking probabilities for the worst-case XT benchmark, FF, BF, and the proposed Score Function RMCSA algorithm in COST239.

Since SDM-EONs are expected to carry high amounts of data, analysis of bandwidth blocking probability (BBP) [3] gives better insight into the performance analysis. We begin with the COST239 topology. Fig. 1 shows the calculated bandwidth blocking probability at each load comparing the worst case XT benchmark (W-XT) implemented under First Fit, the modified spectrum allocation benchmarks, XT-aware First Fit (FF) and Best Fit (BF), and the proposed Score Function (SF) approach RMCSA algorithm. The FF and BF are also subjected to the XT constraint for a fair comparison with the proposed approach. Results show that the bandwidth blocking is lower in the proposed approach. This is because, at any given time, the algorithm tries to find a block that balances the XT and fragmentation-causing capabilities. The chance of successful allocation is higher in the proposed approach despite changes in the request sizes. With any given candidate spectral block, the algorithm considers how much fragmentation it could cause that can lead to the possibility of rejection of bigger-sized requests in the future. The performance difference is larger with the FF than the BF since BF inherently causes lower fragmentation than FF. However, as seen in Section II, the proposed SF captures the fragmentation effect better than the BF and also includes XT information. The blocking is always higher in the worst-case XT case since all neighbor cores are considered to be active at any given time. The proposed SF approach more than halves the bandwidth blocking probability for lower traffic loads compared with the conventional W-XT method.

Fig. 2 compares the blocking probability between the benchmark W-XT, XT-aware FF, XT-aware BF, and the proposed approach. The blocking is lower for the SF using the similar reasoning given for Fig. 1. The conventional W-XT method results in a blocking probability of more than twice that of the proposed SF method for all traffic loads tested. The proposed approach helps to make the spectrum decision that is not just looking at the current possibility of acceptance but also aims at minimizing the rejection of future requests, should they be provisioned on the same spectral positions on the adjacent

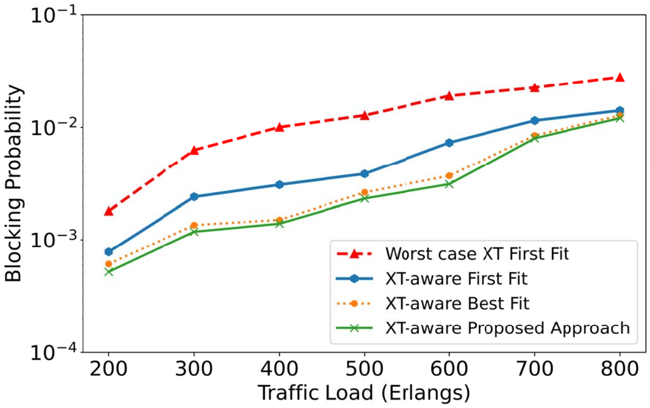

Fig. 2. Blocking probabilities for the worst-case XT benchmark, FF, BF, and the proposed Score Function RMCSA algorithm in COST239.

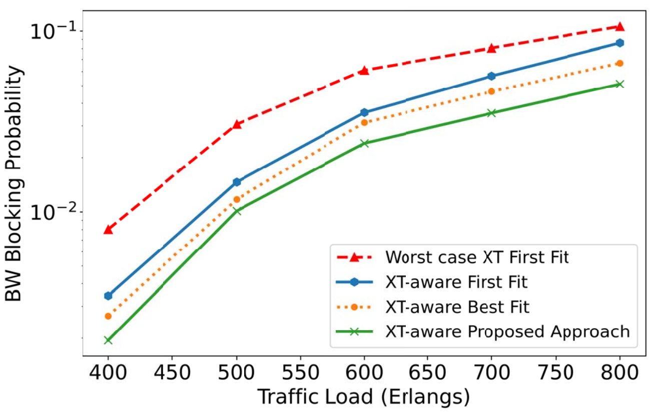

Fig. 3. Bandwidth blocking probabilities for the worst-case XT benchmark, FF, BF, and the proposed Score Function RMCSA algorithm in NSFNET.

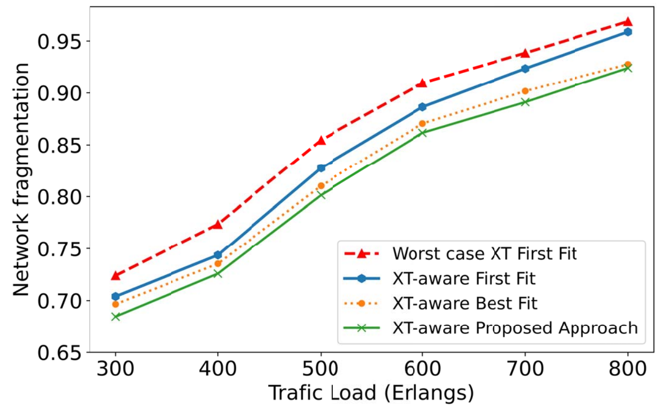

Fig. 4. Network fragmentation for the worst-case XT benchmark, FF, BF, and the proposed Score Function RMCSA algorithm in NSFNET.

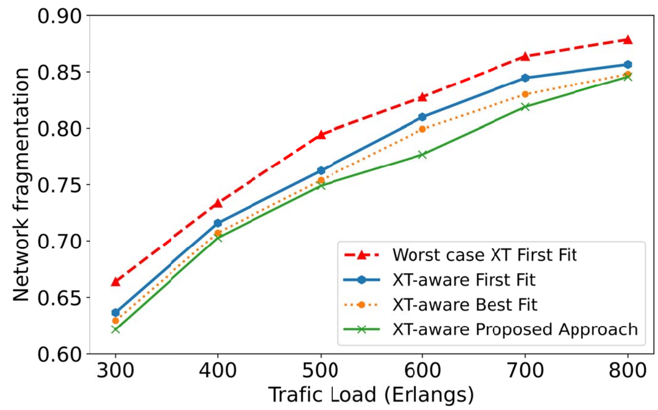

Fig. 5. Network fragmentation for the worst-case XT benchmark, FF, BF, and the proposed Score Function RMCSA algorithm in COST239.

cores or on different positions on the same core. Although the FF and BF tend to minimize fragmentation, they don't consider inter-core XT in the allocation decision, except for accepting or rejecting on the basis of the XT constraint given in (1).

The proposed algorithm is tested further on a 14-node and 21-link NSFNET topology to verify its effectiveness. Fig. 3 shows the bandwidth blocking probability obtained for W-XT, XT-aware FF, XT-aware BF, and the proposed approach. The proposed approach is able to maintain lower bandwidth blocking at higher loads as well, thus affirming the better performance of our algorithm.

Figs. 4 and 5 show the network fragmentation values for W-XT, XT-aware FF and BF, and the proposed approach as the traffic load is increased in NSFNET and COST239 networks, respectively. In both networks, the proposed approach is able to maintain lower overall fragmentation than the benchmarks. This is expected since the proposed approach better quantifies the creation of fragments. We also observe that the W-XT approach leads to the highest fragmentation among the methods tested. In the W-XT method, candidate blocks are evaluated by considering all neighbor cores as active, thereby increasing the chance of failure of (1). This failure leads to an increase in spectrum fragments as compared to XT-aware FF, BF, and the proposed SF approach.

IV. Conclusions

A crosstalk and fragmentation-aware RMCSA algorithm is proposed that relies on a weighted score function that qualitatively incorporates the effects of the expected XT and the expected fragmentation on existing and upcoming traffic. The efficacy of the approach is observed in the results, showing that choosing the spectrum blocks according to the proposed Score Function helps balance the XT and network fragmentation levels in SDM-EONs.

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